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Analysis of Frequency Thermal Characteristics of Pipe-embedded Concrete Radiant Floors Based on FDFD method

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Abstract

Pipe-embedded concrete radiant floor is widely used for air-conditioning by mainly radiant heat transfer duo to its high energy efficiency and the potential for using low-grade energy source. In this study, two-dimensional frequency-domain finite-difference (FDFD) models are built to predict the frequency thermal responses of pipe-embedded concrete radiant floors with insulations of different thicknesses. Corresponding CFD models are built to validate the accuracy of the developed FDFD models. The result shows the predictions by the FDFD model and CFD model may agree very well in the frequency range of concern. The effects of insulation thickness on the thermal responses of pipe-embedded concrete radiant floors are also analyzed by using the validated FDFD models.

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Keyword: Pipe-embedded concrete radiant floor; Low temperature difference heat transfer; Frequency-domain finite-difference (FDFD) model; Frequency thermal characteristics

1. Introduction

The pipe-embedded radiant floor heating and cooling system is one kind of thermally activated building systems (TABS) [1-3]. It is increasingly used for better comfort and higher energy efficiency when compared with traditional air systems [4-6]. Accurate dynamic prediction model of this pipe-embedded construction is very important for the designers to specify and size energy-efficient radaint floor systems, and to improve indoor thermal comfort [7] .

Frequency-domain finite-difference(FDFD) method has been widely applied in electromagnetic fields [8,9], and its applications on heat transfer are found increasingly in recent years[10]. This study presents the application of FDFD method for analyzing the frequency thermal characteristics of pipe-embedded concrete radiant floors. With this method, the effects of insulation thickness on the thermal responses of pipe-embedded concrete radiant floors are also presented.

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2. Development of the FDFD model of the pipe-embedded concrete radiant floor

The cross-section of a pipe-embedded radiant floor construction is divided into a finite number of cells using the finite-difference method and each cell has four resistances and one capacitance, in which linear systems are assumed.

All the heat capacity and mass of each cell is concentrated on its node (i.e., its centre), and the temperature distribution in each cell is uniform. The heat fluxes and temperatures of the cells are all expressed in complex form. The frequency thermal responses of the pipe-embedded radiant floor can be obtained by solving the energy balance equation of each cell simultaneously in frequency domain.

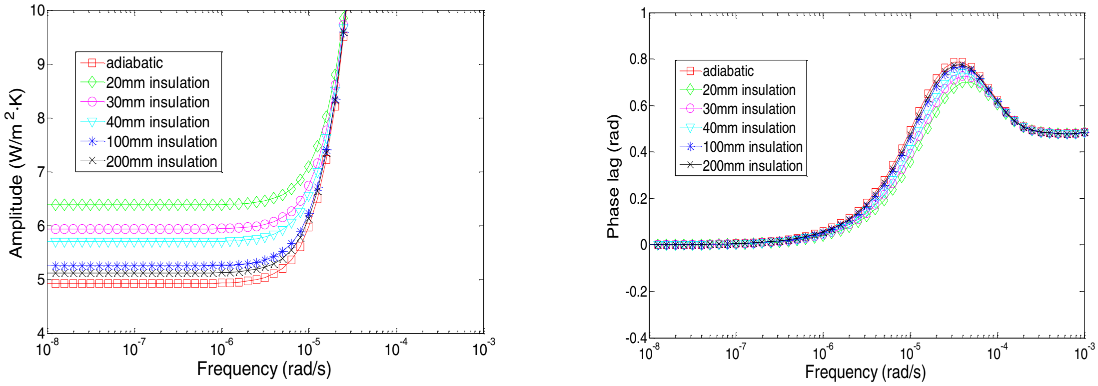
3. Comparison between FDFD model and CFD model

In this study, CFD method is also used to develop a virtual experiment model of pipe-embedded concrete radiant floor acting as a virtual experiment rig for validating the FDFD model of this structure. The results demonstrate that the predictions of the FDFD and CFD models agree very well, and the FDFD model can provide accurate prediction. In addition, the FDFD model is less much time-consuming than the CFD model.

5. Frequency thermal responses of pipe-embedded radiant floors

To study the effect of insulation thickness on the thermal characteristics of pipe–embedded concrete radiant floors, the frequency thermal responses of the pipe-embedded floors with insulation of various thicknesses are calculated by the validated FDFD model. Usually, the insulations with the thicknesses of 20mm, 30mm and 40mm are often used in practical engineering. The extreme thicknesses of 100mm and 200mm are also used in this study for performance calculation for comparison.

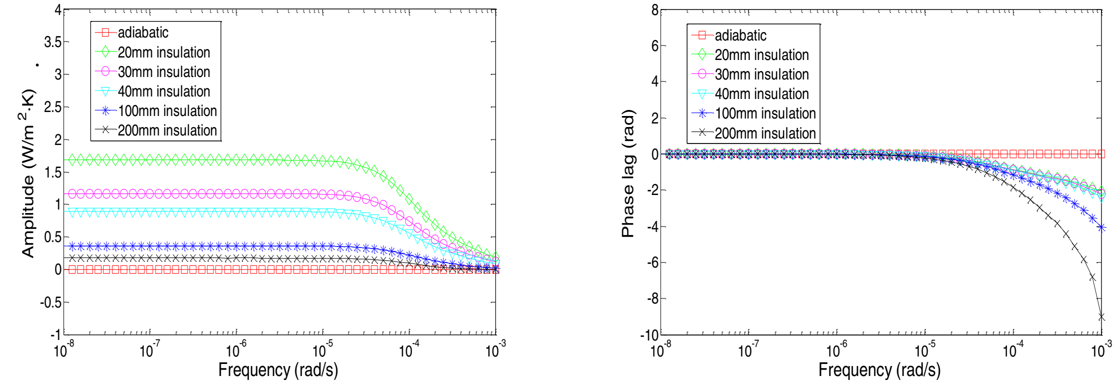
Figure 1 and 2 show the calculated frequency thermal responses of the internal pipe surface and the bottom floor surface for various insulation thicknesses respectively when the internal pipe surface of the radiant floor is exposed to a harmonic temperature wave with the amplitude of 1, the phase angle of 0, and the frequency of ω, and the temperatures of the remained two surfaces (upper floor surface and bottom floor surface) are assumed to be zero.



(a) (b)

Figure 1 Frequency thermal responses on the internal pipe surface

As can be seen in Figure 1(a), there exists an obvious effect of the insulation thickness on the heat flux amplitudes of the internal pipe surface in low frequency region. This is due to that the increased insulation prevents the heat loss through the bottom surface. However, the increased insulation doesn't have an obvious effect on the heat flux phase lags of the internal pipe surface as shown in Figure 1(b), which can be explained by the light-weight characteristic of insulation material. The change of the insulation thickness from 20mm to 200mm results in 20% decrease in the heat flux amplitudes of the internal pipe surface, which means that the increase of insulation thickness has a significant effect on the heat transfer between the water pipe and the floor mass.



(a) (b)

Figure 2 Frequency heat flux responses on the bottom floor surface

As shown in Figure 2(a), the change of the insulation thickness from 20mm to 200mm results in obvious decrease in the heat flux amplitudes of the bottom floor surface in low frequency region. And the heat flux amplitudes of the bottom floor surface for the insulation thickness 20mm,30mm,40mm,100mm and 200mm are 26% ,19%, 16%, 7% and 4% of the heat flux amplitudes of the internal pipe surface respectively. This means that there still exists an obvious heat or coolth loss from the bottom floor surface even for the insulation of 40mm. Figure 2(b) presents the heat flux phase lags on the bottom floor surface, and obvious effects of the insulation thickness on the phase lag may be observed in high frequency region. This point agrees with that about 20%~30% heat loss through the bottom surface with the conventional insulation thickness from 20mm to 40mm [11] .

As can also be found from the above results for a pipe-embedded radiant floor with a given insulation thickness, the frequency thermal response of these three surfaces remains basically unchanged as the frequency changes in low frequency region. The phase lags in low frequency region are approximately equal to 0. In high frequency region, the frequency thermal responses of these three surfaces change rapidly as the frequency changes. Therefore, the heat transfer of pipe-embedded radiant floor in high frequency region should be calculated by dynamic calculation method instead of steady one when the water pipe temperature has an obvious change.

6. Conclusion

Two-dimensional FDFD model is developed for the pipe-embedded radiant floor to predict its frequency thermal responses. For validation of the FDFD model for frequency characteristics analysis, CFD model is developed to calculate the thermal responses of this structure for reference. The results show that the thermal responses of these three surfaces of the pipe-embedded floor system predicted by

FDFD model agree well with that predicted by CFD model. In addition, FDFD model is more efficient and needs much less time than CFD model. FDFD model can predict these frequency thermal responses directly and conveniently.

With the validated FDFD model, the frequency thermal responses of the pipe-embedded radiant floor with insulation of different thicknesses are predicted. The effect of insulation thickness on the frequency thermal responses is further analyzed. The results show that the frequency thermal responses of these three surfaces remain basically unchanged in low frequency region while they may change significantly in high frequency region. However, the insulation thickness has obvious effects on the frequency thermal responses of upper floor surface, especially significant effects on the frequency thermal responses of the internal pipe surface and the bottom floor surface. Although the insulation of 20mm, 30mm, and 40mm are often used in practical engineering, the heat and coolth loss cannot be ignored. When the period of disturbances is considered lager than one day or half of one day especially in heating season, the dynamic effects of the insulation on these frequency thermal responses can be neglected.

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